

A summary of current trends and probable future trends in climate and climate-driven processes in the Giant Sequoia National Monument and the neighboring Sierra Nevada.

Hugh Safford, Regional Ecologist, USDA Forest Service, Pacific Southwest Region.
hughsafford@fs.fed.us; 707-562-8934. Date: January 27, 2010

I. Local trends in climate over the past century

The data presented in this section are derived primarily from two weather stations with long-term meteorological records from the general area of the Giant Sequoia National Monument (“GSNM”). The longest quasi-continuous weather record is provided by the Huntington Lake station (1915-2009; WRCC 2009), which is about 25 miles (40 km) north of the northern border of the GSNM, and lies at 7020 feet above sea level (2830 m), at approximately 37° 13.76’ N, 119° 14.63’ W. The elevation of the station and surrounding vegetation are representative of the area of the GSNM within which management activities are proposed. The Huntington Lake weather record is missing annual data from the years 1915, 1948, 2003, and 2009, and precipitation data are missing from 1962-1974 (WRCC 2009). A 70-year dataset (1940-2009) is also available from the Grants Grove station in Sequoia-Kings Canyon National Parks (“SEKI-NP”) (6580 feet asl; 36° 44.2’ N, 118° 57.8’ W), which is found in the center of the northern portion of the GSNM (WRCC 2009). In this document, reference is also made to weather records from two other SEKI-NP stations: the Giant Forest station (6370 feet asl; 36° 33.83’ N, 118° 46.82’ W), which is found between the northern and southern portions of the GSNM and which provides a 47-yr record from 1921-1968; and the nearby Lodgepole station, (6750 feet asl; 36° 36.33’ N, 118° 44.47’ W), which provides a 41-yr record from 1968-2009 (WRCC 2009).

Temperature

Over the last 94 years, mean annual temperature at the Huntington Lake station has risen by about 1.8° Fahrenheit (Fig. 1; values from regression equation). This trend is driven by a highly significant increase in mean minimum (i.e., nighttime) temperatures, which have risen by 4° F since 1915. At the beginning of the record, the annual average of the monthly mean minima was below the freezing point, but it is now more than three degrees above the freezing point (Fig. 1). The 70-year record from Grants Grove shows a similar story, but with even more pronounced warming (Fig. 2). Mean annual temperatures at Grants Grove have risen by about 2.7° F since 1940, and nighttime mean minima have risen by about 5° F; the mean maxima have not changed. The occurrence of nighttime freezing temperatures has been decreasing over the last century. For example, at the beginning of the Huntington Lake data record six to seven months in a year could be expected to have average nighttime temperatures that fell below freezing. Today the average is closer to five months, and the trend is strongly downward (Fig. 3).

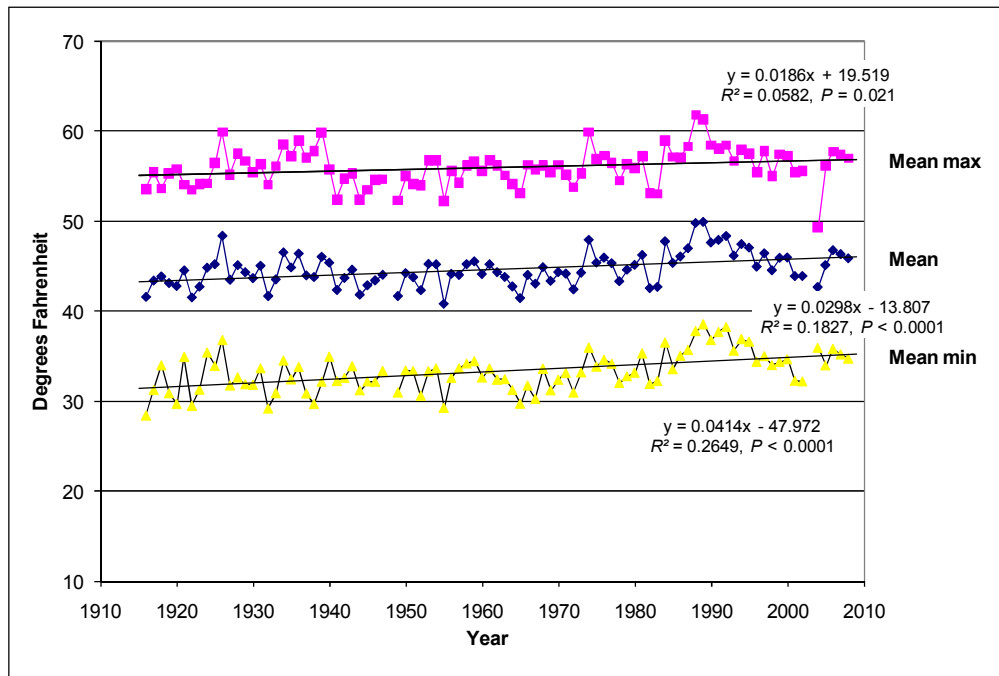


Figure 1. Annual mean, mean maximum, and mean minimum temperatures at Huntington Lake, California, 1915-2009. Trend lines fit with simple linear regression, no transformations employed. Data from WRCC 2009.

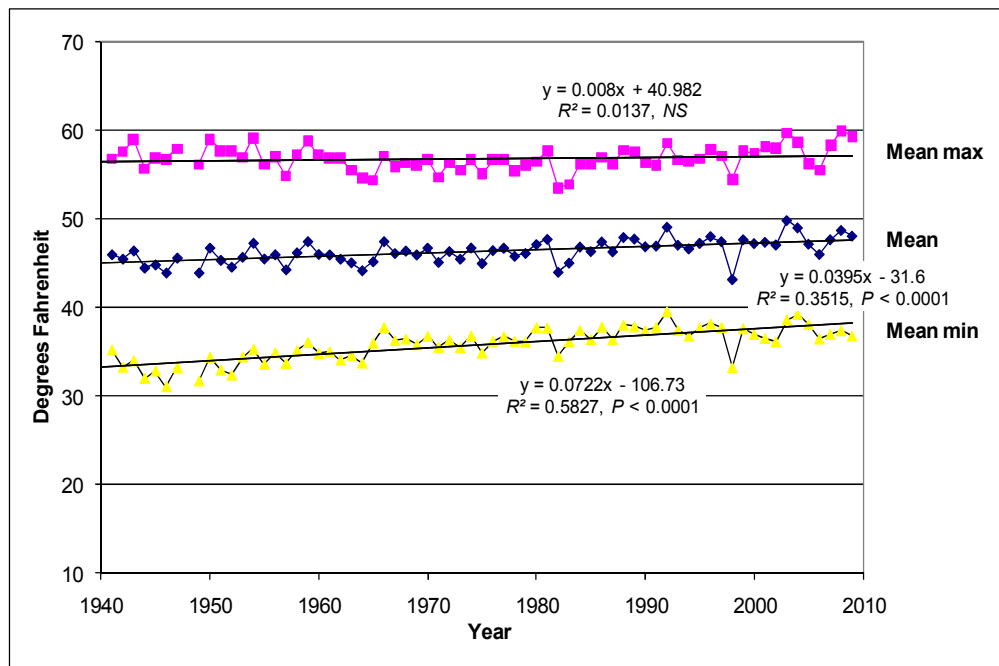


Figure 2. Annual mean, mean maximum, and mean minimum temperatures at Grants Grove, California, 1940-2009. Trend lines fit with simple linear regression, no transformations employed. Data from WRCC 2009.

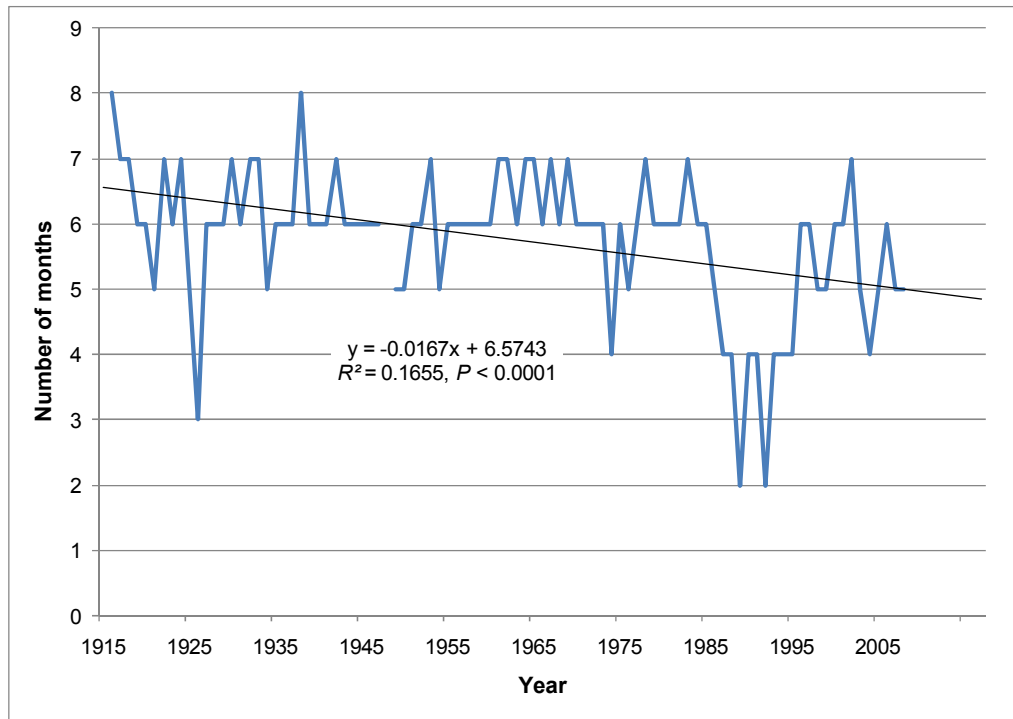


Figure 3. Number of months with the monthly mean minimum temperature remaining below freezing at Huntington Lake, California, 1915-2009. Trend line fit with simple linear regression. Data from WRCC 2009.

Precipitation

Local and subregional precipitation trends in the Sierra Nevada range from negative to positive (WRCC 2009), and trends at even nearby stations can vary widely. The 94-year trend in precipitation at Huntington Lake is shown in Fig. 3. Average annual precipitation has risen greatly over the period (from a predicted 25.6 inches per year in 1915 to 45.6 inches per year in 2009), but there is very high interannual variability, such that the value predicted by the regression line in Fig. 2 is rarely representative of the actual annual mean. In addition, the great increase predicted by the regression line is driven to a notable extent by a number of extreme precipitation years, such as 1982, 1983, and 1996. In contrast to the Huntington Lake station, the Grants Grove station in SEKI-NP shows no statistically discernable change in mean annual precipitation between 1940 and 2009 (Fig. 4), and the Giant Forest station in SEKI-NP shows no change between 1921 and 1968 (WRCC 2009). The Lodgepole station in SEKI-NP also shows no significant change in mean annual precipitation between 1969 and 2009.

As is the case with precipitation itself, interannual variability in precipitation varies from station to station. At Huntington Lake, the 5-yr standard deviation of annual precipitation is rising strongly over time (Fig. 4), which demonstrates that year-to-year variability in precipitation has increased over the course of the last century. Further evidence of high variability in recent annual precipitation sums can be seen in the last thirty years of records from Huntington Lake: 13 of the 20 wettest years have occurred since 1980 and the 10 wettest have all occurred since 1978, but 2007 and 2009 were among the five

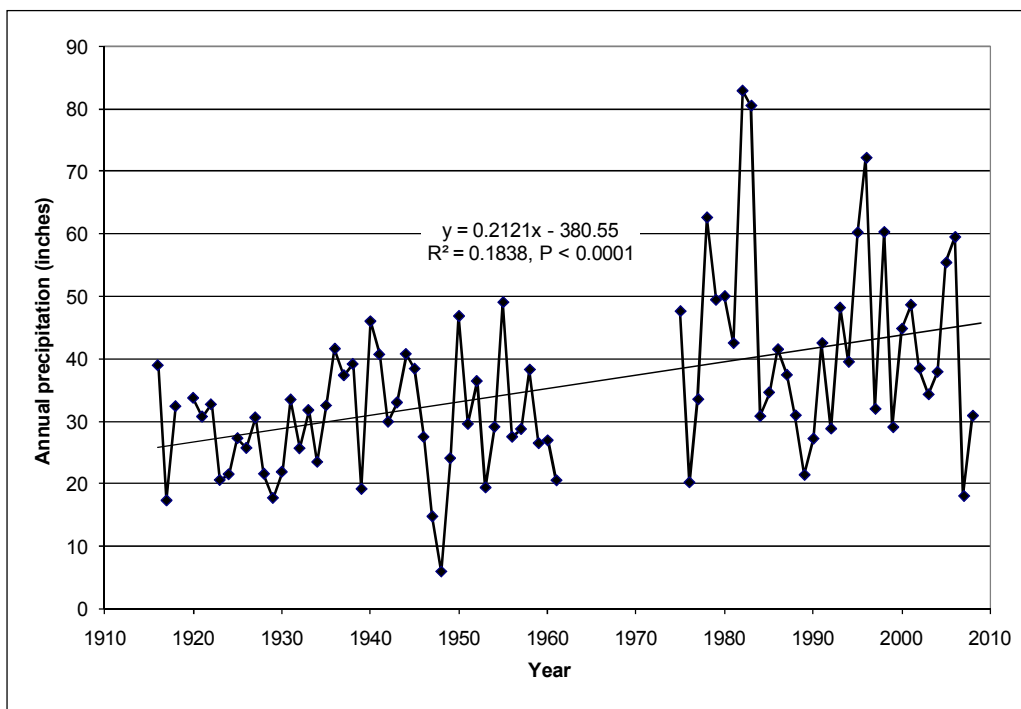


Figure 3. Mean annual precipitation at Huntington Lake, California, 1915-2009. Trendline fit with simple linear regression, no transformations employed. Data from WRCC 2009.

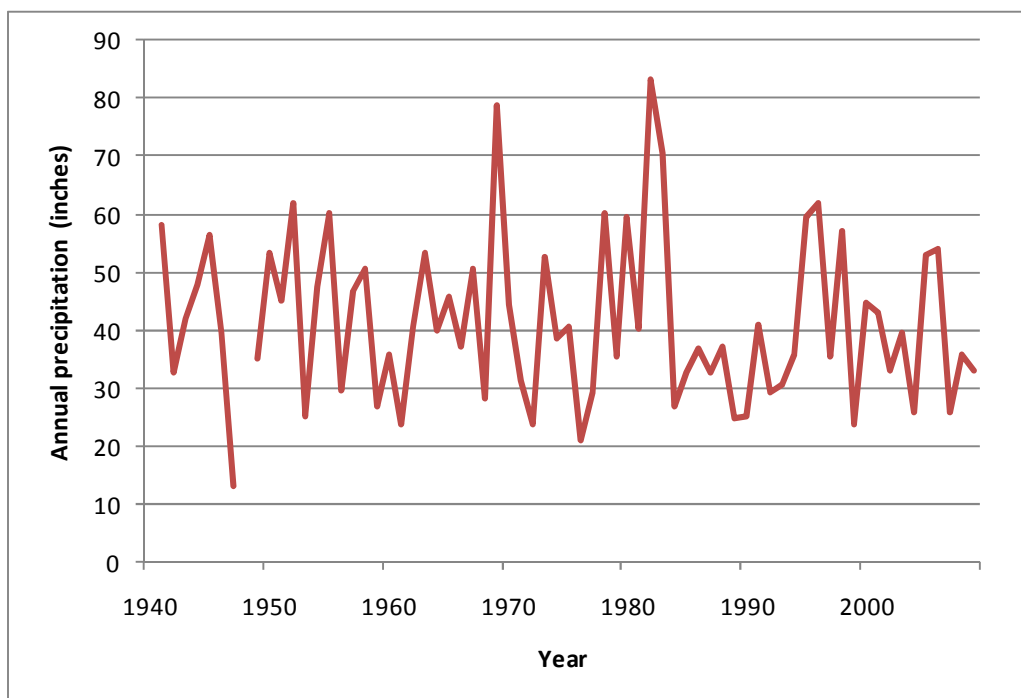


Figure 4. Mean annual precipitation at Grants Grove, California, 1940-2009. There is no statistically significant trend in the time series. Data from WRCC 2009.

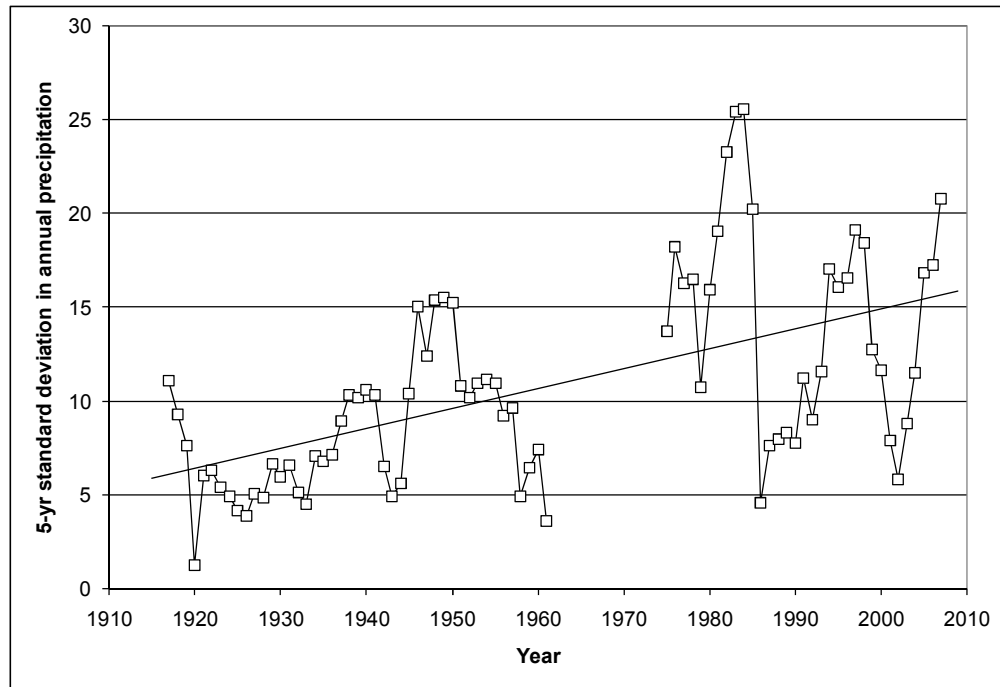


Figure 4. Five-year standard deviations in annual precipitation at Huntington Lake, California, 1915-2009. Data from WRCC 2009.

driest years on record (2009 has incomplete data in the station record and is not shown in Figure 3). Interannual variability also increased at the Giant Forest station between 1921 and 1968, but it showed no long-term change between 1940 and 2009 at the Grants Grove station and it decreased between 1968 and 2009 at the Lodgepole station (not shown; WRCC 2009).

Because the southern Sierra Nevada is so high, the diminishing snowpack and snow-water equivalent trends seen across the rest of California have not yet occurred in many higher elevation river basins (Fig. 5). Like precipitation in general however, there are great differences in snowfall trends between different southern Sierra Nevada sites. For example, between 1915 and 1973 mean annual snowfall at Huntington Lake rose from around 200 inches to over 250 inches (predicted from linear regression, $R^2 = 0.065$, $P < 0.01$; WRCC 2009) (the record for snowfall from Huntington Lake is incomplete and ends in 1972), while the records from Grants Grove (1940-2009) and Lodgepole (1968-2009) in SEKI-NP show no statistical trends in annual snowfall totals (WRCC 2009).

II. Regional trends over the last century linked to climate change

Hydrology

Stewart et al. (2005) showed that the onset of spring thaw in most major streams in the central Sierra Nevada occurred 5-30 days earlier in 2002 than in 1948, and peak streamflow (measured as the center of mass annual flow) occurred 5-15 days earlier. During the same period, March flows in the studied streams were mostly higher by 5-20%, but June flows were mostly lower by the same amount; overall spring and early

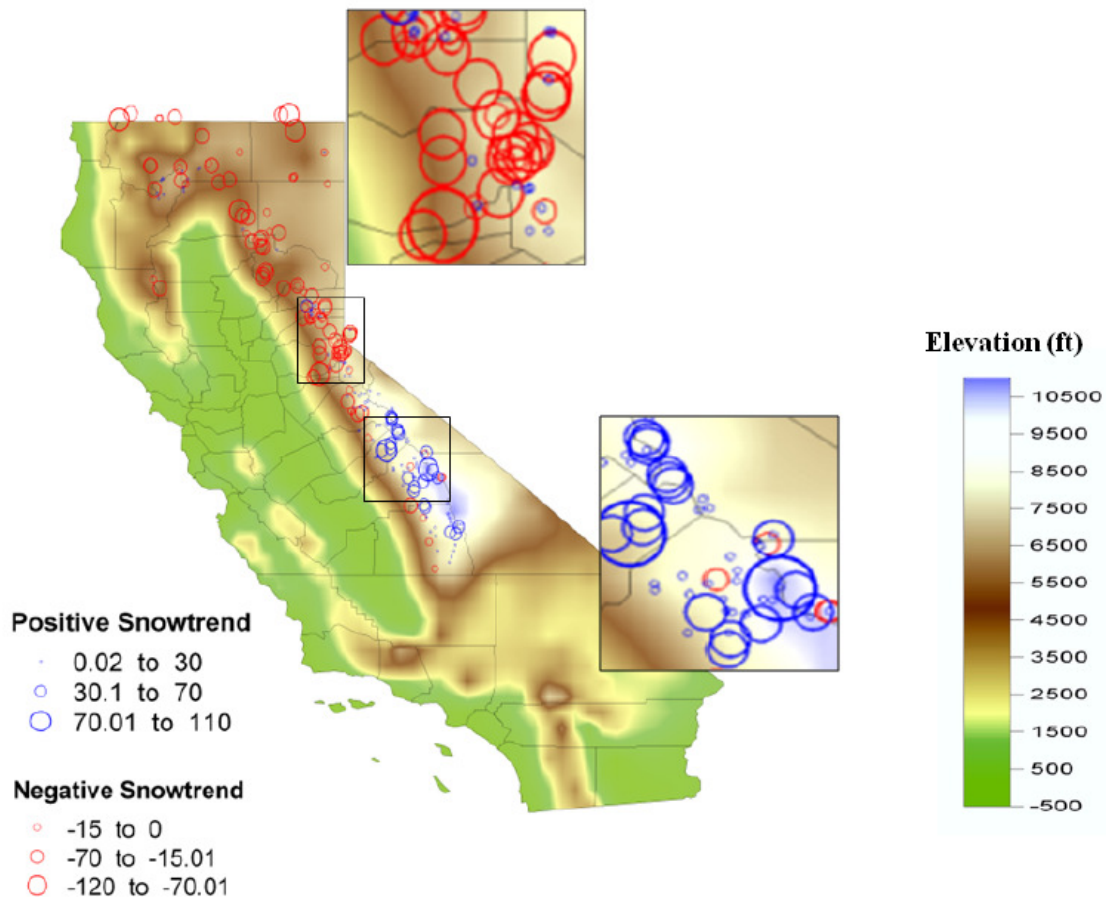


Figure 5. Trends in the amount of water contained in the snowpack (“snow water equivalent”) on April 1, for the period 1950-1997. Red circles indicate percent decrease in snow water, blue circles indicate increase in snow water. From Moser et al. (2009).

summer streamflow was down in most studied streams. Rising winter and spring temperatures appear to be the primary driver of these patterns (Stewart et al. 2005).

Forest fires

Data on forest fire frequency, size, total area burned, and severity all show strong increases in the Sierra Nevada over the last two to three decades. Westerling et al. (2006) showed that increasing frequencies of large fires (>1000 acres) across the western United States since the 1980’s were strongly linked to increasing temperatures and earlier spring snowmelt. The Sierra Nevada was one of two geographic areas of especially increased fire activity, which Westerling et al. (2006) ascribed to an interaction between climate and increased fuels due to fire suppression. Westerling et al. (2006) also identified the Sierra Nevada as being one of the geographic regions most likely to see further increases in fire activity due to future increases in temperature.

Miller et al. (2009) showed that mean and maximum fire size, and total burned area in the Sierra Nevada have increased strongly between the early 1980's and 2007. Climatic variables explain very little of the pattern in fire size and area in the early 20th century, but 35-50% of the pattern in the last 25 years. The mean size of escaped fires in the Sierra Nevada was about 750 acres until the late 1970's, but the most recent ten-year average has climbed to about 1100 acres. Miller et al. (2009) also showed that forest fire severity (a measure of the effect of fire on vegetation) rose strongly during the period 1984-2007, with the pattern centered in middle elevation conifer forests. Fires at the beginning of the record burned at an average of about 17% high (stand-replacing) severity, while the average for the last ten-year period was 30%. Miller et al. (2009) found that both climate change and increasing forest fuels were necessary to explain the patterns they analyzed.

Forest structure

Fire suppression has been practiced as a federal policy since 1935. Pre-Euroamerican fire frequencies in high elevation forests such as red fir (>50 years in most places) and subalpine forest (>100 years) were long enough that fire suppression has had little or no impact on ecological patterns or processes (Miller et al. 2009). Higher elevation forests are also much more remote, less likely to have economic uses, and are often protected in Wilderness Areas and National Parks, so impacts by logging or recreation use are minimal. Subalpine tree growth has been shown to be strongly influenced by higher precipitation and warm summers (Graumlich 1991). Long-term changes in stand structure in higher elevation forests are thus more likely to represent responses to changes in exogenous factors like climate.

In the early 1930's, the Forest Service mapped vegetation on National Forest lands in the Sierra Nevada, and sampled thousands of vegetation plots (Wieslander 1935). Bouldin (1999) compared the Wieslander plots with the modern FIA inventory and described changes in forest structure for the Sierra Nevada from Yosemite National Park to the Plumas National Forest, i.e. to the north of the GSNM. In red fir forest, Bouldin (1999) found that densities of young trees had increased by about 40% between 1935 and 1992, but densities of large trees had decreased by 50% during the same period. In old-growth stands, overall densities and basal areas were higher, and the number of plots in the red fir zone dominated by shade-tolerant species increased at the expense of species like Jeffrey pine and western white pine. In old-growth subalpine forests, Bouldin (1999) found that young mountain hemlock, a shade-tolerant species, was increasing in density and basal area while larger western white pine was decreasing. In whitebark pine stands, overall density was increasing due to increased recruitment of young trees, but species composition had not changed. Lodgepole pine appears to be responding favorably to increased warming and/or increased precipitation throughout the subalpine forest.

Bouldin (1999) also studied mortality patterns in the 1935 and 1992 datasets. He found that mortality rates had increased in red fir, with the greatest increases in the smaller size-classes. At the same time, in subalpine forests, lodgepole pine, western white pine, and mountain hemlock all showed decreases in mortality. The subalpine zone was the only forest type Bouldin (1999) studied where mortality had not greatly increased since the 1935 inventory. This suggests that climate change (warming, plus higher precipitation in

some cases) is actually making conditions better for some tree species in this stressful environment.

Van Mantgem et al. (2009) recently documented widespread increases in tree mortality in old-growth forests across the west, including in the Sierra Nevada. Their plots had not experienced increases in density or basal area during the 15-40 year period between first and last census. The highest mortality rates were documented in the Sierra Nevada, and in middle elevation forests (3300-6700 feet). Higher elevation forests (>6700 feet) showed the lowest mortality rates, corroborating the Bouldin (1999) findings. Van Mantgem et al. (2009) ascribed the mortality patterns they analyzed to regional climate warming and associated drought stress.

Comparisons of the 1930's Wieslander vegetation inventories and map with modern vegetation maps and inventories show large changes in the distribution of many Sierra Nevada vegetation types over the last 70-80 years (Fig. 6; Bouldin 1999, Moser et al. 2009, Thorne and Safford, unpub. data). The principal trends are (1) loss of yellow pine-dominated forest, (2) increase in the area of forest dominated by shade-tolerant conifers (especially fir species), (3) loss of blue oak woodland, (4) increase in hardwood-dominated forests, (5) loss of subalpine and alpine vegetation, and (6) expansion of subalpine trees into previous permanent snowfields (Fig. 6). Trends (4) through (6) appear to have a strong connection to climate warming, while trends (1) through (3) are mostly the product of human management choices, including logging, fire suppression, and urban expansion.

III. Future predictions

Climate

As of today, no published climate change or vegetation change modeling has been carried out for the GSNM. Indeed, few future-climate modeling efforts have treated areas as restricted as the State of California. The principal limiting factor is the spatial scale of the General Circulation Models (GCMs) that are used to simulate future climate scenarios. Most GCMs produce raster outputs with pixels that are 10,000's of km² in area. To be used at finer scales, these outputs must be downscaled using a series of algorithms and assumptions – these finer-scale secondary products currently provide the most credible sources we have for estimating potential outcomes of long-term climate change for California. Another complication is the extent to which GCMs disagree with respect to the probable outcomes of climate change. For example, a recent comparison of 21 published GCM outputs that included California found that estimates of future precipitation ranged from a 26% increase per 1° C increase in temperature to an 8% decrease (Gutowski et al. 2000, Hakkarinen and Smith 2003). That said, there was some broad consensus: all of the reviewed GCMs predicted warming temperatures for California, and 13 of 21 predicted higher precipitation (three showed no change and five predicted decreases). According to Dettinger (2005), the most common prediction among the most recent models (which are considerably more complex and, ideally, more credible) is temperature warming by about 9 degrees F by 2100, with precipitation

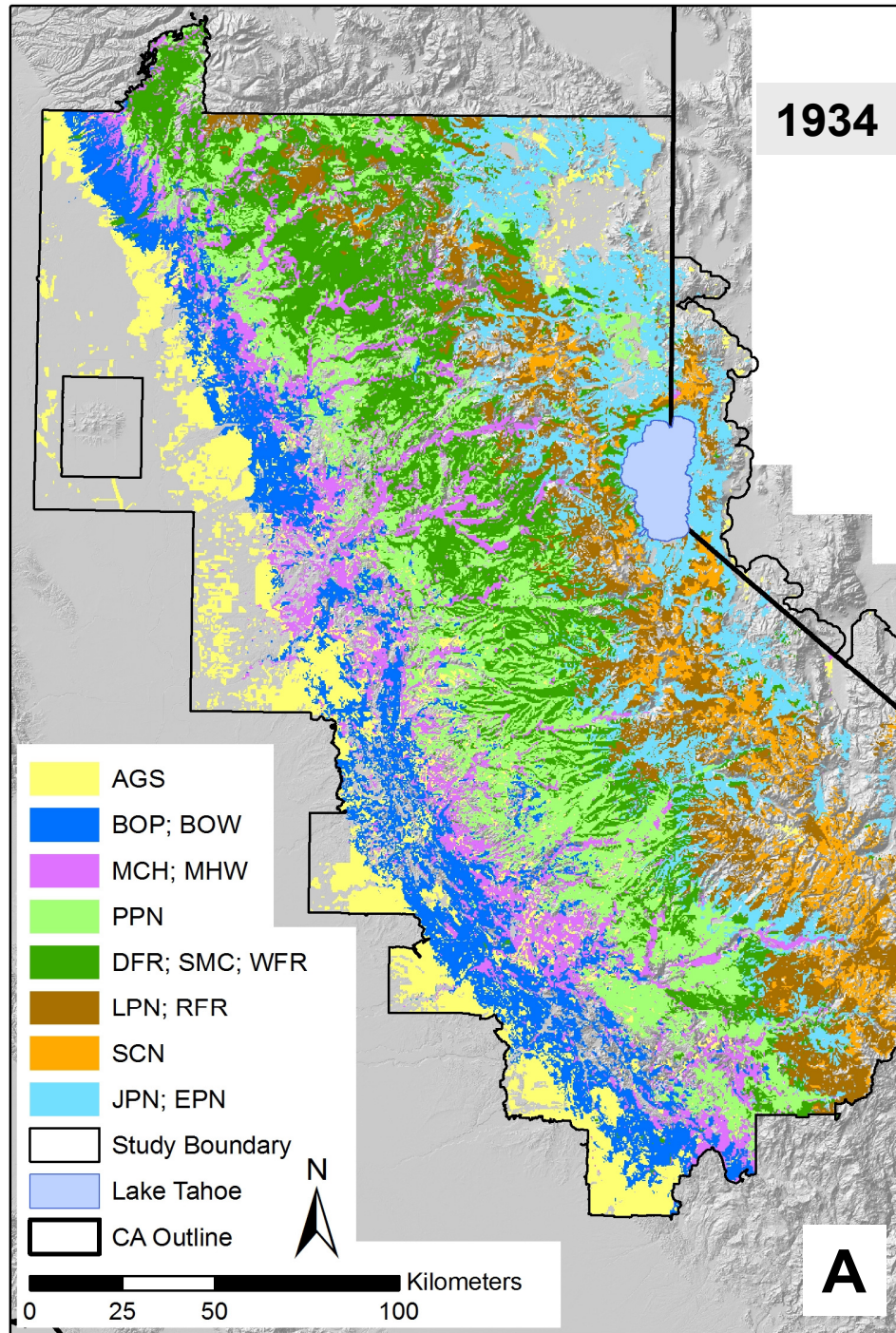


Figure 6. (A) Distribution of major vegetation types in the central and northern Sierra Nevada in the period 1932-1936. Mapped by the US Forest Service “Wieslander” mapping project. Maps digitized and vegetation types cross-walked to CWHR type by UC-Davis Information Center for the Environment. AGS = agriculture; BOP = blue oak/foothill pine; BOW = blue oak woodland; MCH = mixed conifer hardwood; MHW = mixed hardwood; PPN = ponderosa pine; DFR = Douglas-fir; SMC = Sierra mixed conifer; WFR = white fir; LPN = lodgepole pine; RFR = red fir; SCN = Subalpine conifer; JPN = Jeffrey pine; EPN = eastside pine. GSNM is located just south of the mapped area, in and around the letter “A”.

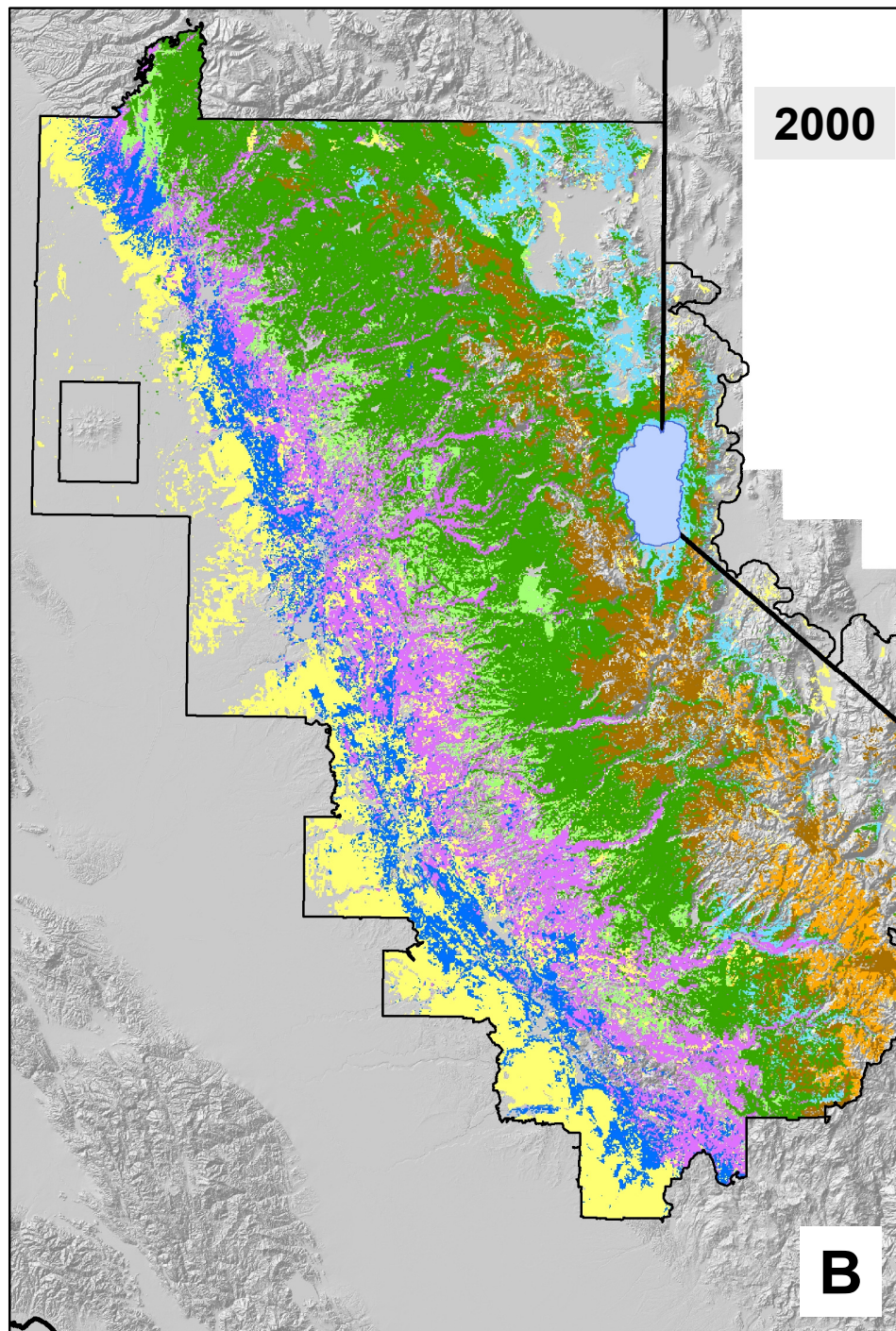


Figure 6. (B) Distribution of major vegetation types in the central and northern Sierra Nevada in 2000. Mapped by the US Forest Service Pacific Southwest Region Remote Sensing Laboratory. See Fig. IIi (A) for key and scale. The major patterns of change between 1934 and 2000 are: (1) loss of yellow pine (ponderosa and Jeffrey pine) dominated forest; (2) expansion of shade-tolerant conifers (DFR, WFR, SMC); (3) loss of blue oak woodland; (4) increase in hardwood-dominated forests; (5) loss of subalpine and alpine vegetation. GSNM is located just south of the mapped area, in and around the letter “B”.

remaining similar or slightly reduced compared to today. Most models agreed that summers will be drier than they are currently, regardless of levels of annual precipitation.

The most widely cited of the recent modeling efforts is probably Hayhoe et al. (2005). Hayhoe et al. (2005) used two contrasting GCMs (much warmer and wetter, vs. somewhat warmer and drier) under low and high greenhouse gas emissions scenarios to make projections of climate change impact for California over the next century. By 2100, under all GCM-emissions scenarios, April 1 snowpack was down by -22% to -93% in the 6,700-10,000 feet elevation belt, and the date of peak snowmelt was projected to occur from 3 to 24 days earlier in the season. Average temperatures were projected to increase by 2 to 4 degrees F in the winter, and 4-8 degrees in the summer. Finally, three of the four GCM-emissions scenarios employed by Hayhoe et al. (2005) predicted strong decreases in annual precipitation by 2100, ranging from -91 to -157%; the remaining scenario predicted a 38% increase.

Although the southern Sierra Nevada snowpack has generally remained steady (or risen) over the past half-century (Fig. 5; Moser et al. 2009), continued warming is likely to erode the temperature buffer that the high southern Sierra Nevada enjoys. Most modeling projects a continuously increasing rain:snow ratio and earlier runoff dates for the next century, with decreased snowpack and growing-season stream flow the end results even in the higher river basins (Miller et al. 2003, Moser et al. 2009).

Hydrology

Miller et al. (2003) modeled future hydrological changes in California as a function of two contrasting GCMs (the same GCMs used in Hayhoe et al. [2005] and Lenihan et al. [2003; see below]) and a variety of scenarios intermediate to the GCMs. Miller et al. (2003) found that annual streamflow volumes were strongly dependent on the precipitation scenario, but changes in seasonal runoff were more complex. Predicted spring and summer runoff was lower in all of the California river basins they modeled, except where precipitation was greatly increased, in which case runoff was unchanged from today (Miller et al. 2003). Runoff in the winter and early spring was predicted to be higher under most of the climate scenarios because higher temperatures cause snow to melt earlier. Flood potential in California rivers that are fed principally by snowmelt (i.e., higher elevation streams) was predicted to increase under all scenarios of climate change, principally due to earlier dates of peak daily flows and the increase in the proportion of precipitation falling as rain.

These increases in peak daily flows are predicted under all climate change scenarios, including those assuming reduced precipitation (Miller et al. 2003). The predicted increase in peak flow was most pronounced in higher elevation river basins, due to the greater reliance on snowmelt. If precipitation does increase, streamflow volumes during peak runoff could greatly increase. Under the wettest climate scenario modeled by Miller et al. (2003), by 2100 the volume of flow during the highest flow days could more than double in many Sierra Nevada rivers. This would result in a substantial increase in flood risk in flood-prone areas in the Central Valley. According to Miller et al. (2003), increased flood risk is a high probability outcome of the continuation of current climate change trends, because temperature, not precipitation, is the main driver of higher peak

runoff. If climate change leads not only to an increase in average precipitation but also a shift to more extreme precipitation, then peak flows would be expected to increase even more.

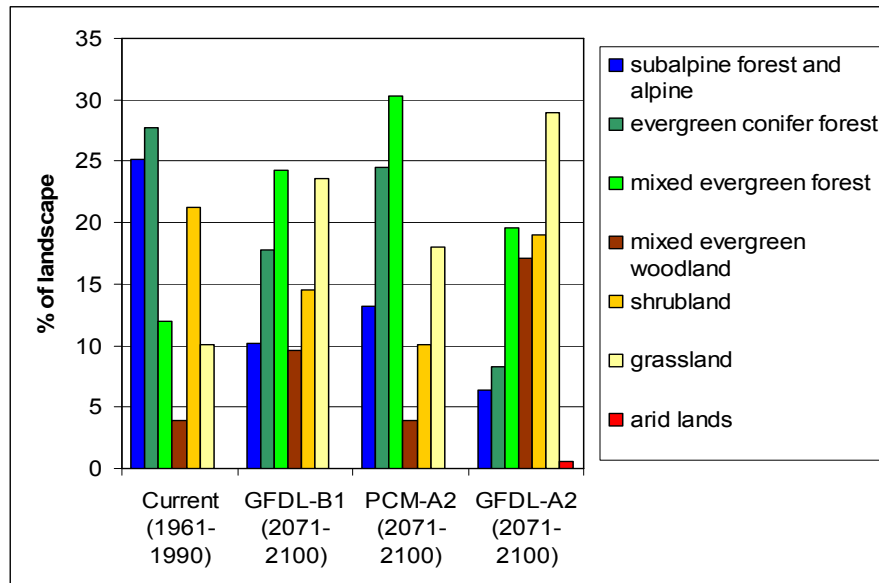
Vegetation

Lenihan et al. (2003, 2008) used a dynamic ecosystem model (“MC1”) which estimates the distribution and the productivity of terrestrial ecosystems such as forests, grasslands, and deserts across a grid of 100 km² cells. To this date, this is the highest resolution at which a model of this kind has been applied in California, but it is not of high enough resolution to be applied to the GSNM as a unit. Based on their modeling results, Lenihan et al. (2003, 2008) projected that forest types and other vegetation dominated by woody plants in California would migrate to higher elevations as warmer temperatures make those areas suitable for colonization and survival. For example, with higher temperatures and a longer growing season, the area occupied by subalpine and alpine vegetation was predicted to decrease as evergreen conifer forests and shrublands migrate to higher altitudes (Fig. 7). Under their “wetter” future scenarios (i.e., slightly wetter or similar to today), Lenihan et al. (2003, 2008) projected a general expansion of forests in the Sierra Nevada, especially north of the GSNM and at higher elevations. With higher rainfall and higher nighttime minimum temperatures, broadleaf trees (especially oak species) were predicted to replace conifer-dominated forests in many parts of the low and middle elevation Sierra Nevada. Under their drier future scenarios, Lenihan et al. (2003, 2008) predicted that grasslands would expand, and that increases in the extent of tree-dominated vegetation would be minimal. An expansion of shrublands into conifer types was also predicted, due to drought and increases in fire frequency and severity (see below), but increasing fire frequency in the southern Sierra Nevada may replace much low to middle elevation shrubland with grassland (Fig. 7). Hayhoe et al. (2005) also used the MC1 ecosystem model to predict vegetation and ecosystem changes under a number of different future greenhouse gas emissions scenarios. Their results were qualitatively similar to the Lenihan et al. (2003, 2008) results.

Fire

The combination of warmer climate with higher CO₂ fertilization will likely cause more frequent and more extensive fires throughout western North America (Price and Rind 1994, Flannigan et al. 2000); fire responds rapidly to changes in climate and will likely overshadow the direct effects of climate change on tree species distributions and migrations (Flannigan et al. 2000, Dale et al. 2001). A temporal pattern of climate-driven increases in fire activity is already apparent in the western United States (Westerling et al. 2006), and modeling studies specific to California expect increased fire activity to persist and possibly accelerate under most future climate scenarios, due to increased growth of fuels under higher CO₂ (and in some cases precipitation), decreased fuel moistures from warmer dry season temperatures, and possibly increased thundercell activity (Price and Rind 1994, Miller and Urban 1999, Lenihan et al. 2003, 2008; Westerling and Bryant 2006). By 2100, Lenihan et al.’s (2003, 2008) simulations suggest a c. 5% to 8% increase in annual burned area across California, depending on the climate scenario. Increased frequencies and/or intensities of fire in coniferous forest in California will almost certainly drive changes in tree species compositions (Lenihan et al. 2003, 2008), and will likely reduce the size and extent of late-successional refugia (USFS and

M261E: Sierra Nevada



M261F: Sierra Nevada Foothills

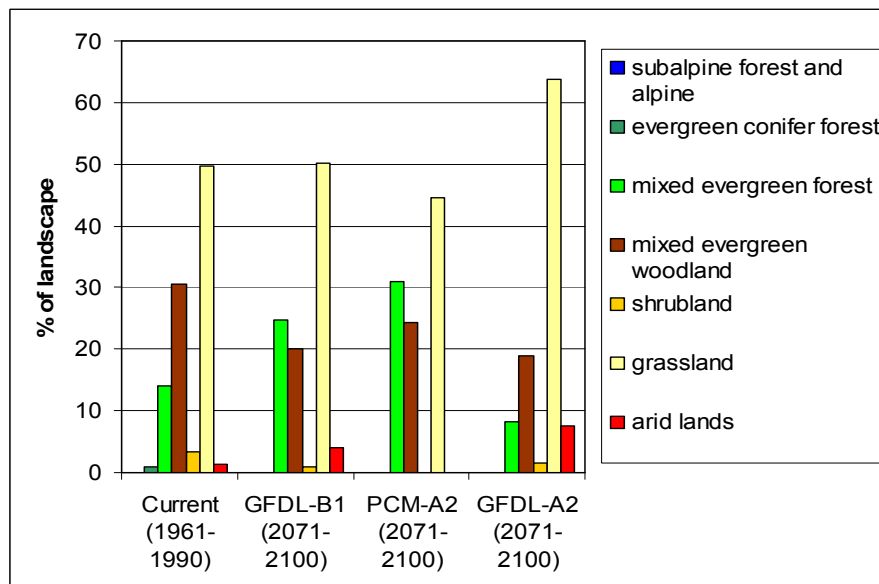


Figure 7. MC1 outputs for the Sierra Nevada and SN Foothills Ecological Sections, current vs. future projections of vegetation extent. These Ecological Sections include most of the Sierra Nevada west slope. The GFDL-B1 scenario = moderately drier than today, with a moderate temp. increase (<5.5° F); PCM-A2 = similar ppt. to today, with <5.5° temp. increase; GFDL-A2 = much drier than today and much warmer (>7.2° higher) All scenarios project significant loss of subalpine and alpine vegetation. Most scenarios project lower cover of shrubland (including west side chaparral and east side sagebrush), due principally to increasing frequencies and extent of fire. Large increases in the hardwood component of forests are projected in all scenarios except for the hot-dry scenario in the Foothills. Large increases in cover of grassland are projected for the Sierra Nevada section. The drier scenarios project moderate expansion of arid lands. In the Sierra Nevada section, conifer forest decreases in cover under all scenarios. Data from Lenihan et al. (2008).

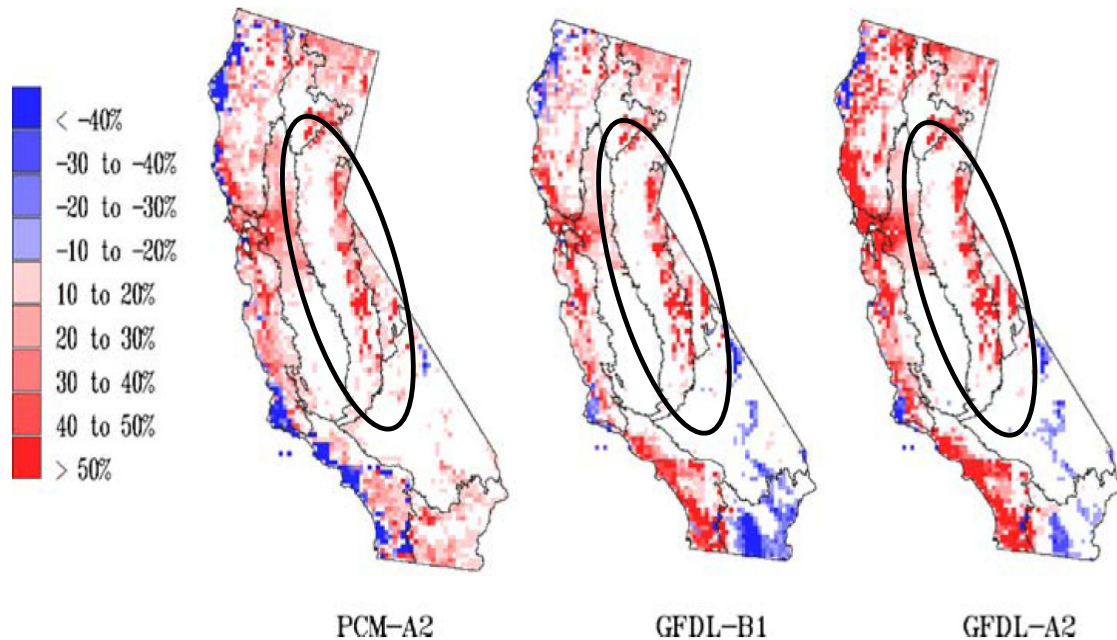


Figure 8. Percent change in projected mean annual area burned for the 2050-2099 period relative to the mean annual area burned for the historical period (1895-2003). Sierra Nevada is circled. Figure from Lenihan et al. (2008). See Fig. 5 for description of the climate and emissions scenarios (PCM-A2, GFDL-B1, GFDL-A2).

BLM 1994, McKenzie et al. 2004). Thus, if fire becomes more active under future climates, there may be significant repercussions for old growth forest and old growth-dependent flora and fauna.

A key question is to what extent future fire regimes in montane California will be characterized by either more or less severe fire than is currently (or was historically) the case. Fire regimes are driven principally by the effects of weather/climate and fuel type and availability (Bond and van Wilgen 1996). 70 years of effective fire suppression in the American West have led to fuel-rich conditions that are conducive to intense forest fires that remove significant amounts of biomass (McKelvey et al. 1996, Arno and Fiedler 2005, Miller et al. 2009), and most future climate modeling predicts climatic conditions that will likely exacerbate these conditions. Basing their analysis on two GCMs under the conditions of doubled atmospheric CO₂ and increased annual precipitation, Flannigan et al. (2000) predicted that mean fire severity in California (measured by difficulty of control) would increase by about 10% averaged across the state. Vegetation growth models that incorporate rising atmospheric CO₂ show an expansion of woody vegetation on many western landscapes (Lenihan et al. 2003, 2008; Hayhoe et al. 2005), which could feedback into increased fuel biomass and connectivity and more intense (and thus more severe) fires. Use of paleoecological analogies also suggests that parts of the Pacific Northwest (including northern California) could experience more severe fire conditions under warmer, more CO₂-rich climates (Whitlock et al., 2003). Fire frequency and severity (or size) are usually assumed to be inversely related (Pickett and White

1985), and a number of researchers have demonstrated this relationship for Sierra Nevada forests (e.g. Swetnam 1993, Miller and Urban 1999), but if fuels grow more rapidly *and* dry more rapidly – as is predicted under many future climate scenarios – then both severity and frequency may increase. In this scenario, profound vegetation type conversion is all but inevitable. Lenihan et al.'s (2003, 2008) results for fire intensity predict that large proportions of the Sierra Nevada landscape may see mean fire intensities increase over current conditions by the end of the century, with the actual change in intensity depending on future precipitation patterns (Fig. 8).

Literature Cited

- Arno, S. F., and C. E. Fiedler. 2005. Mimicking nature's fire. Restoring fire-prone forests in the West. Island Press, Washington, DC, USA.
- Bond, W. J., and B. W. van Wilgen. 1996. Fire and plants. Chapman and Hall, London, England.
- Bouldin, J. 1999. Twentieth-century changes in forests of the Sierra Nevada, California. Ph.D. dissertation, University of California, Davis.
- Dale, V. H., L. A. Joyce, S. McNulty, R. P. Neilson, M. P. Ayres, M. D. Flannigan, P. J. Hanson, L. C. Irland, A. E. Lugo, C. J. Peterson, D. Simberloff, F. J. Swanson, B. J. Stocks, and B. M. Wotton. 2001. Climate change and forest disturbances. *BioScience* 51: 723-734.
- Dettinger, M. D. 2005. From climate-change spaghetti to climate-change distributions for 21st century California. *San Francisco Estuary and Watershed Science* Vol. 3, Issue 1, (March 2005), Article 4. <http://repositories.cdlib.org/jmie/sfews/vol3/iss1/art4>
- Field, C., G. Dailey, F. Davis, S. Gaines, P. Matson, J. Melack, and N. Miller. 1999. Confronting climate change in California: ecological impacts on the Golden State. Report of the Union of Concerned Scientists and the Ecological Society of America. UCS Publications, Cambridge, Massachusetts, USA.
- Flannigan M. D., B. J. Stocks, and B. M. Wotton. 2000. Climate change and forest fires. *Science of the Total Environment* 262: 221–229.
- Graumlich, L. J. 1991. Subalpine tree growth, climate, and increasing CO₂: an assessment of recent growth trends. *Ecology* 72: 1-11.
- Gutowski, W. J., Z. Pan, C. J. Anderson, R. W. Arritt, F. Otieno, E. S. Takle, J. H. Christensen, and O. B. Christensen. 2000. What RCM data are available for California impacts modeling? California Energy Commission Workshop on Climate Change Scenarios for California, 12-13 June, 2000. California Energy Commission, Sacramento, CA, USA.

Hakkarinen, C., and J. Smith. 2003. Appendix I. Climate scenarios for a California Energy Commission study of the potential effects of climate change on California: summary of a June 12-13, 2000, workshop. *In* Global Climate Change and California: Potential Implications for Ecosystems, Health, and the Economy. EPRI (Electric Power Research Institute), Palo Alto, CA, USA. 38 pp.

Hayhoe, K., et al. (18 co-authors). 2004. Emissions pathways, climate change, and impacts on California. *Proceedings of the National Academy of Sciences* 101: 12422-12427.

Lenihan, J. M., R. Drapek, D. Bachelet and R. P. Neilson. 2003. Climate change effects on vegetation distribution, carbon, and fire in California. *Ecological Applications* 13: 1667-1681.

Lenihan, J. M., D. Bachelet, R. P. Neilson, and R. Drapek. 2008. Response of vegetation distribution, ecosystem productivity, and fire to climate change scenarios for California. *Climate Change* 87 (Suppl. 1): S215-S230.

McKelvey, K.S., C. N. Skinner, C. Chang, D. C. Erman, S. J. Husari, D. J. Parsons, J. W. van Wagendonk, J.W., and C. W. Weatherspoon. 1996. An overview of fire in the Sierra Nevada. *In* Sierra Nevada Ecosystem Project: final report to Congress. Vol. II, Assessments and scientific basis for management options. University of California, Centers for Water and Wildland Resources, Davis, CA, USA. Pp. 1033-1040.

McKenzie, D., Z. Gedalof, D. L. Peterson and P. Mote. 2004. Climatic change, wildfire, and conservation. *Conservation Biology* 18: 890-902.

Miller, C., and D. Urban. 1999. Forest pattern, fire and climatic change in the Sierra Nevada. *Ecosystems* 2: 76-87

Miller, J. D., H. D. Safford, M. Crimmins, and A. E. Thode. 2009. Quantitative evidence for increasing forest fire severity in the Sierra Nevada and southern Cascade Mountains, California and Nevada, USA. *Ecosystems* 12: 16-32

Miller, N. L., K. E. Bashford and E. Strem. 2003b. Potential impacts of climate change on California hydrology. *Journal of the American Water Resources Association* 39: 771-784.

Moser, S., G. Franco, S. Pittiglio, W. Chou, D. Cayan. 2009. The future is now: An update on climate change science impacts and response options for California. California Climate Change Center Report CEC-500-2008-071, May 2009. California Energy Commission, Sacramento, CA.

Pickett, S. T. A., and P. S. White. 1985. *The Ecology of Natural Disturbance and Patch Dynamics*. Academic Press, New York, NY, USA

Price, C., and D. Rind. 1994. The impact of a 2 x CO₂ climate on lightning-caused fires. *Journal of Climate* 7: 1484-1494.

Stephens, S. L., and S. J. Gill. 2005. Forest structure and mortality in an old growth Jeffrey pine-mixed conifer forest in north-western Mexico. *Forest Ecology and Management* 205: 15-20.

Stewart, I.T., D. R. Cayan, and M. D. Dettinger. 2005. Changes toward earlier streamflow timing across western North America. *Journal of Climate* 18: 1136-1155.

Swetnam, T. W. 1993. Fire history and climate change in giant sequoia groves. *Science* 262: 885-889.

Taylor, A. H. 2004. Identifying forest reference conditions on early cut-over lands, Lake Tahoe Basin, USA. *Ecological Applications* 14: 1903-1920.

TERC. 2008. Tahoe State of the Lake Report. Tahoe Environmental Research Center, University of California, Davis, CA.

USFS and BLM. 1994. Record of Decision for amendment to Forest Service and Bureau of Land Management planning documents within the range of the northern spotted owl. USDA Forest Service and USDI Bureau of Land Management, Portland, OR, USA.

Van Mantgem, P. J., et al. (10 co-authors). 2009. Widespread increase of tree mortality rates in the western United States. *Science* 323: 521-524.

Westerling, A. L., and B. Bryant. 2006. Climate change and wildfire in and around California: fire modeling and loss modeling. Report from the California Climate Change Center to the California Energy Commission. CEC-500-2006-190-SF.

Westerling, A. L., H. Hidalgo, D. R. Cayan, and T. Swetnam. 2006. Warming and earlier spring increases western U.S. forest wildfire activity. *Science*, 6 July, 2006 /10.1126/ science.1128834

Whitlock, C., S. L. Shafer, and J. Marlon. 2003. The role of vegetation change in shaping past and future fire regimes in the northwest U.S. and the implications for ecosystem management. *Forest Ecology and Management* 178: 5-21.

Wieslander, A. E. 1935. A vegetation type map of California. *Madroño* 3: 140-144.

WRCC. 2009. California climate data archive. Data obtained from Western Regional Climate Center, <http://www.calclim.dri.edu/ccacoop.html> (last accessed on 26 January, 2009).